Photometric standard stars in the BVI system in a wide field centered on the spiral galaxy NGC 300.[1]

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ABSTRACT

Based on 13 nights of observations of four fields in NGC 300, we have set up an extensive sequence of stars with accurate BVI photometry covering a relatively large (25 x 25 arcmin) region centered on this galaxy. This sequence of standard stars is very useful for calibrating the photometry of variable stars and other objects in NGC 300 and other galaxies obtained from wide field mosaic images. Our standard star list contains B, V and I measurements for 390 stars. The accuracy of the zero points in the V filter and B-V color is better than 0.02 mag, and about 0.03 mag for the V-I color. We found very good agreement between our measurements and those previously obtained by Walker for 26 stars near NGC 300.

Subject headings: techniques:photometric—galaxies:photometry—galaxies:individual (NGC 300)

[1]Based on observations obtained with the 1.3-m Warsaw telescope at the Las Campanas Observatory of the Carnegie Institution of Washington and with the 2.2-m ESO/MPI telescope at the European Southern Observatory

1. Introduction

We are currently engaged in a detailed study of the stellar populations in the southern spiral galaxy NGC 300. This object belongs to the Sculptor Group and is, at a distance of about 2 Mpc, one of the closest spirals, close enough to be resolved into stars even near the nucleus on high-resolution ground-based images. As a first step, we recently investigated the OB associations content of NGC 300 (Pietrzyński et al. 2001) from wide field images obtained at the ESO 2.2-m telescope, which cover a 34 x 34 arcmin field centered on the galaxy. Based on the same data 117 Cepheids and 12 Cepheid candidates were found (Pietrzyński et al. 2002), extending the previous work of Graham (1984) who discovered the first Cepheids in NGC 300 from photographic plates, and Freedman et al. (1992) who derived the first CCD light curves of 12 of these Cepheids, which were used to derive a preliminary distance to the galaxy. The newly discovered Cepheids will be very useful to obtain a truly accurate distance to this galaxy, and to calibrate the effect of metallicity on the Cepheid period-luminosity relation in optical (BVRI) bandpasses. In a parallel project, we analyzed photometric and spectroscopic data for a sample of blue supergiants in NGC 300 with the aim to obtain metal abundances and the metallicity gradient in the disk of NGC 300, and to derive an independent distance estimate from the wind momentum-luminosity relation valid for these stars (Kudritzki et al. 1999). First results of this study have been recently presented by Bresolin et al. (2002).

In order to accurately calibrate the photometric magnitudes of the Cepheids, blue supergiants, and of thousands of other stars in our wide field images, we need a sufficient number of high-quality photometric standard stars which are distributed over the whole area we are observing, span a broad range in magnitudes and colors, and extend down to the faint limit of our 1.3 m images. A previous photometric sequence close to NGC 300 has been set up by Graham (1981; photoelectric sequence covering the magnitude range V=9-20), which was later improved by Walker (1988, 1995) from CCD photometry. However, this sequence is covering only a relatively small field (about 6 x 6 arcmin) and contains only a small number of stars with BVI magnitudes (26). This is insufficient for our purpose to provide highly accurate (to 0.02-0.03 mag) BVI magnitudes for thousands of stars in the wide 34 x 34 arcmin field around NGC 300. We therefore decided to set up a new and extensive sequence of accurate standard star magnitudes in this field, well suited for the transformation of data from wide field, mosaic detectors.

2. Observations

We have collected images of NGC 300 through standard BVI filters using the very stable photometric telescope/detector system of the Warsaw 1.3 m telescope at Las Campanas Observatory, which has been used to conduct the OGLE II photometric microlensing survey (Udalski, Kubiak, and Szymański 1997). The telescope was equipped with a 2048 $\times$ 2048 CCD detector. The pixel size was 24 μm, which corresponds to a scale of 0.417 arcsec/pixel. The observations were performed in the "medium" reading mode of the CCD detector. The gain and readout noise were 7.1 electrons/ADU and 6.3 electrons, respectively. More details about the instrumentation setup can be found in Udalski, Kubiak and Szymański (1997). Color equations, and the transformations to the BVI (Johnson-Cousins) standard photometric system are very well established for this system, making it an ideal choice to carry out our programme of setting up a new standard star sequence in NGC 300. In order to cover most of the 34 x 34 arcmin field covered by our ESO wide field images, we observed the four slightly overlapping 15 x 15 arcmin fields shown in Fig. 1. Their coordinates are given in Table 1. During 13 nights in August, September and October 2000 we were able to secure 48 images of these fields (16 in each filter). The journal of these observations is given in Table 2. Exposure times were 900, 750, and 600 s in B, V, and I bands, respectively.

Table 1. Observed fields in NGC 300

Field	RA (J2000)	DEC (J2000)	N_{nights}
F1	$0^h54^m21\overset{s}{.}2$	-37°34′40″	5
F2	$0^h54^m21\overset{s}{.}2$	-37°48′04″	4
F3	$0^h55^m24\overset{s}{.}6$	-37°48′57″	4
F4	$0^h55^m24\overset{s}{.}6$	-37°34′34″	3

Table 2. Journal of observations

Night (2000)	Field(s)	Filters	seeing (arcsec)
Aug02	FI	BVI	1.0
Aug05	FII	BVI	1.1
Aug06	FIII	BVI	0.9
Aug07	FIV	BVI	0.8
Aug30	FI,FII	BVI	1.2
Sep15	FI	BVI	1.1
Sep22	FIII,FIV	BVI	0.7
Sep25	FI	BVI	1.0
Sep26	FII	BVI	1.2
Sep27	FIII	BVI	1.3
Sep28	FI,FIV	BVI	1.3
Sep30	FII	BVI	0.9
Oct03	FIII	BVI	1.2

3. Reductions

The raw frames have been de-biased and flatfielded in the standard way using the IRAF[2] package. Because of the variations of the Point Spread Function (PSF) across the image we divided our frames into four overlapping subframes, on which the PSF can be reasonably assumed as being constant. Then profile photometry with the DAOPHOT and ALLSTAR programs was carried out on each of the subframes. The PSF model was derived iteratively. First 15 candidates from relatively bright and isolated stars were selected and the first approximation of the PSF was derived using DAOPHOT. In the next step we subtracted all neighbouring stars with the ALLSTAR program and derived a new PSF. After three such loops no improvement to the PSF was noted anymore, and we obtained in this way the PSF model which we finally adopted.

In order to convert our profile photometry to the aperture system, aperture corrections were derived for each of the four subframes of any given frame. For this purpose a special procedure was prepared based on DAOPHOT. First the bright, well separated stars were selected (usually 10 per subframe). Then iteratively all neighbouring stars, which could contaminate our measurements were removed and aperture photometry was obtained. Finally, the median of the aperture corrections obtained for these stars was adopted as the aperture correction of the given subframe. With the aperture corrections for all our subframes we transformed the profile photometry to the aperture system and merged them into one file. Relatively large overlapping fields (about 400 pixels) allowed us to check in detail the consistency of our procedure of determining the aperture corrections. Usually more than 20 stars with good photometry (e.g. well suited for comparison purposes) were found to be common to a given two subframes. The mean difference between their aperture photometric magnitudes did not exceed 0.005 mag and the rms was smaller than 0.007 mag. No dependence on brightness, position or color was found.

4. Transformations

4.1. Transformation coefficients

During 10 nights between 3 and 7 Landolt (1992) standard star fields were observed in order to transform our instrumental magnitudes to the standard BVI system. We adopted the following transformations:

[2]IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.

$$
\begin{aligned}
B &= b - 0.041 \times (B - V) + \mathrm{const}_B \\
V &= v - 0.002 \times (V - I) + \mathrm{const}_V \\
I &= i + 0.029 \times (V - I) + \mathrm{const}_I \\
B - V &= 0.959 \times (b - v) + \mathrm{const}_{B-V} \\
V - I &= 0.969 \times (v - i) + \mathrm{const}_{V-I}
\end{aligned}
\tag{1}
$$

where the lower case letters b,v,i denote the aperture instrumental magnitudes normalized to 1 sec exposure time. The color coefficients we used were established during previous extensive observations of a large number of standard stars over the entire season by the OGLE team (e.g. Udalski et al. 1998, 2000). The extinction coefficients were derived for 7 nights. For the other nights the mean extinction coefficients were used. The zero points were determined for all of these 10 nights. The residuals did not exceed 0.03 mag and the zero point was very stable during the whole run (see Fig. 2). The residuals did not show any significant dependence on color, brightness or position on the sky. For remaining 3 nights we assumed mean zero points derived during our run.

In order to test the mean color coefficients provided by the OGLE team we observed, during three nights, a large number of standard stars covering a large range in air mass and color and derived the full set of transformation coefficients from these observations. Then we transformed the instrumental magnitudes using these coefficients and mean ones, and compared the results. The comparison showed that the magnitude difference was smaller than 0.008 mag in each band, demonstrating the high accuracy and stability of the adopted transformation equations.

4.2. Astrometric transformation

To convert pixel positions of stars to the equatorial coordinate system we used the algorithm developed and used in the OGLE project. In brief, using the Digital Sky Survey (DSS) images, fits files slightly larger than our observed fields were extracted. All stars having 200 counts above sky level were detected on these frames and their centroids were calculated. Then, (x,y) pixel coordinates of each star from the DSS images were converted to equatorial coordinates. The resulting (RA,DEC) of our stars were then transformed to (x',y') pixel coordinates on the plane tangent to the celestial sphere at the center of a given field. Finally, the two sets of pixel coordinates (x,y) and (x',y') were tied together using simple third order polynomials. To check the consistency of our transformation we examined the derived coordinates for common stars from overlapping regions. The mean difference of the coordinates derived from the different transformations was found to be about 0.3 arcsec.

5. Results

5.1. BVI photometry

In order to derive final magnitudes and colors, the instrumental magnitudes were normalized to 1 s exposure time and tied to the aperture system (see Section 3). Then they were transformed to the standard BVI system using the coefficients derived as described in Section 4.1. For stars from each of the four fields the mean, and the standard deviations were calculated from all observations (usually 3-5 measurements per star). Fig. 3 presents the standard deviations in B, V and I bands, as a function of magnitude. It is appreciated that there are many stars with relatively small scatter (i.e. good candidates for being local standard stars). To check on the consistency of our photometric data from the 4 different fields we used stars from the overlapping regions. More details of the comparison of the magnitudes and colors of common stars in the four overlapping regions can be found in Table 3. It is seen that the mean differences were usually smaller than 0.02 mag, with a comparable scatter, which indicates that there is no systematic difference between the photometry for our four fields. One should note that the majority of the observations of the four regions were performed during different nights.

Table 3. Results of a comparison of common stars in four overlapping regions

Region	N	$< \delta_{\rm B} >$	$\sigma_{\delta_{\rm B}}$	$< \delta_{\rm V} >$	$\sigma_{\delta_{\rm V}}$	$< \delta_{\rm I} >$	$\sigma_{\delta_{\rm I}}$	$< \delta_{\rm BV} >$	$\sigma_{\delta_{\rm BV}}$	$< \delta_{\rm VI} >$	$\sigma_{\delta_{\rm VI}}$
FI-FII	26	-0.011	0.019	0.000	0.035	-0.027	0.018	0.002	0.014	0.004	0.022
FI-FIV	21	-0.010	0.026	0.003	0.016	-0.016	0.017	-0.010	0.024	0.012	0.021
FII-FIII	19	0.013	0.035	0.006	0.030	-0.001	0.026	0.019	0.018	-0.015	0.028
FIII-FIV	25	-0.003	0.022	0.019	0.020	0.028	0.023	-0.023	0.019	-0.007	0.024

5.2. Comparison with previous results

In order to compare our photometry with that obtained by Walker (1995) for 26 stars in the vicinity of NGC 300, we identified 17 of these stars in our database. Remaining stars from Walker's list were too bright or situated outside our observed field.

The mean difference between Walker's photometry and ours is $\Delta V = 0.002 \pm 0.025$ mag, $\Delta(B-V) = -0.008 \pm 0.025$ mag and $\Delta(V-I) = -0.019 \pm 0.027$ mag. Evidently the results from both studies are in excellent agreement.

Freedman et al. (1992) have obtained CCD BVRI observations for 16 Cepheids in NGC 300. The comparison of our new data on these Cepheids to the Freedman et al. data is presented in Pietrzyński et al. (2002), and the reader is referred to that paper for more details. Here we only note that very good agreement was found. The intensity mean magnitudes of the common Cepheids usually did not differ by more than 0.05 mag. Differences between individual observations at similar phases from the two discussed data sets were typically ± 0.03-0.05 mag (see Fig. 6 in Pietrzyński et al. 2002).

All these comparisons make us conclude that our photometry is very well tied to the standard system. Especially the very small systematic difference between our photometry and the very well calibrated sequence of standard stars of Walker is gratifying. Unfortunately all stars observed by Walker (1995) were located in only one (F II) of our four fields. Taking into account that typically the differences in photometry between our fields are about 0.01 mag (see Table 3) we estimate that our new standard star magnitudes are accurate to better than 0.02 mag in V and B-V, and about 0.03 mag in the case of V-I.

5.3. BVI photometric sequence

The main goal of this paper is the presentation of an extensive list of secondary standard stars covering a large area around NGC 300, well suited for the absolute calibration of data obtained with wide field, mosaic detectors. Having a large number of stars with accurate magnitudes and colors over the whole area of a given mosaic detector (usually the field of view is about 0.5 x 0.5 square degrees) one can easily transform the observations from all the chips into the standard system, avoiding problems with possible differences in the color coefficients, zero points etc. between the various CCDs of the mosaic camera.

To filter out appropriate standard stars, we need to exclude spurious stars detected in the wings of saturated objects, stars with their photometry affected by saturation, stars too close to the edges of the frames, stars being seriously blended, non-stellar objects, and possible variable stars. In order to weed out any such potential problem stars from our sample, we applied the following selection criteria:

1) A star must have at least 2 measurements
2) Standard deviation in V, I and V-I $<$0.05 mag, in B and B-V $<$ 0.07 mag
3) Distance from the edge of a chip must be at least 10 arcsec.
4) Counts must be less than 90 % of the detector range.

As a next step, we visually examined the light curves for all the stars passing the selection criteria using a database constructed from 29 nights of observations of NGC 300 with the ESO WFI imager. All stars showing evidence for possible variability were rejected.

Alltogether 390 stars passed our selection process and entered into the final list of standards which is presented in Table 4. These stars span the following range in brightness and colors: 14.2 $<$ V $<$ 22.0, -0.35 $<$ B-V $<$ 1.94, -0.35 $<$ V-I $<$ 3.26. Information about typical standard deviations for our standard stars in different bands as a function of V magnitude is given in Table 5.

6. Summary

We have obtained accurate BVI photometry for a large number of stars located in a relatively large (25 x 25 arcmin) field centered on NGC 300. The photometric zero points are accurate to 0.02 mag in V and B-V and to 0.03 mag in V-I. From our database, we have selected the stars with the most reliable and accurate photometry which form our final catalog of 390 secondary standard stars in NGC 300. These stars cover a very large range in brightness and color. We have already used these standard stars for our recent photometric work on the stellar populations in NGC 300, and we believe that the new catalog will be very useful for researchers observing this particular galaxy or any other objects in this part of the sky with modern wide field CCD mosaic detectors.

We intend to continue our observations of NGC 300 in order to improve and extend our list of secondary standard stars in this field.

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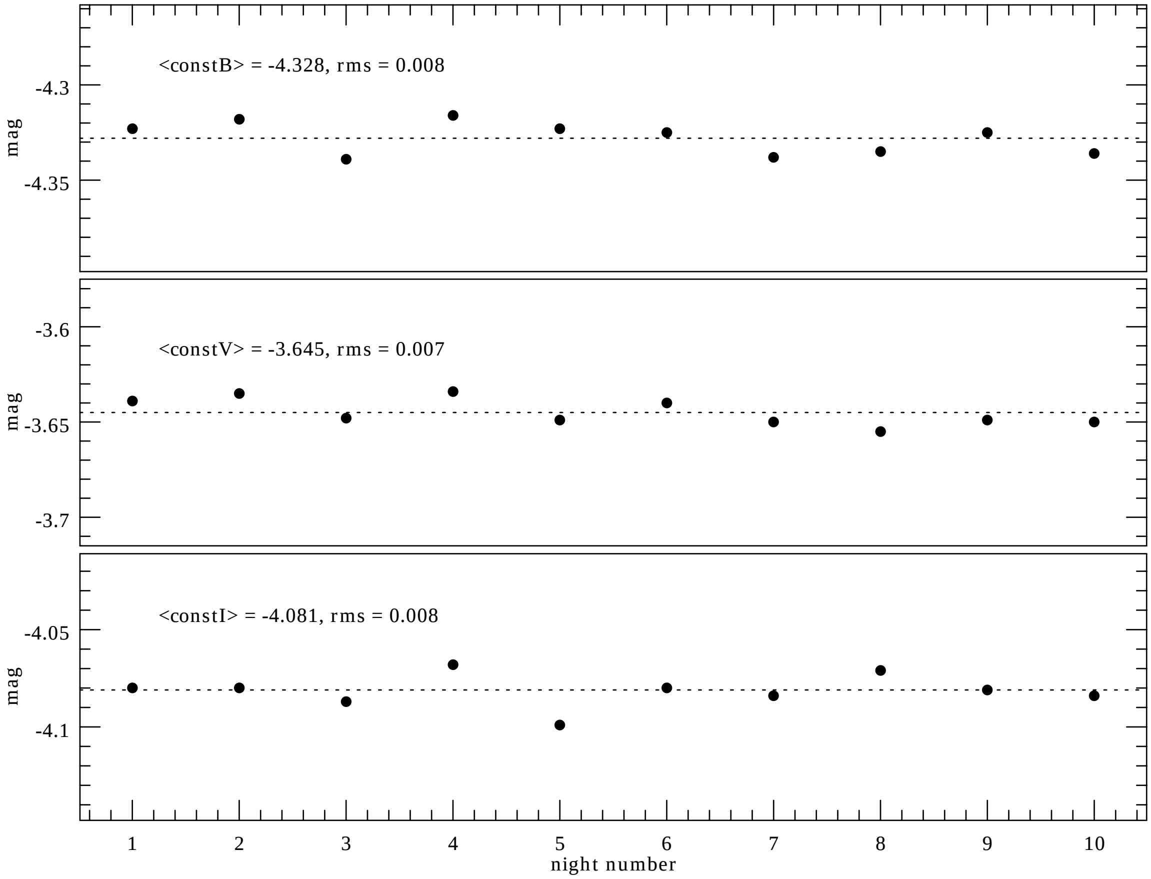
Fig. 1.— Observed fields in NGC 300. Displayed region corresponds to about 34 x 34 arcmin on the sky. North is up and east to the left.

Fig. 2.— The variation of the photometric zero points in the B,V and I filters over our observing nights

Fig. 3.— Standard deviation of brightness as a function of magnitude, in different bands, for all observed stars in NGC 300

Table 5. Mean standard deviations of standard stars as a function of their V magnitude.

Magnitude range in V	$<\sigma_{\rm B}>$	$<\sigma_{\rm V}>$	$<\sigma_{\rm I}>$	N stars
14-15	0.014	0.012	0.013	10
15-16	0.016	0.014	0.014	14
16-17	0.015	0.016	0.015	21
17-18	0.018	0.014	0.013	33
18-19	0.018	0.016	0.015	49
19-20	0.020	0.018	0.018	100
20-21	0.022	0.020	0.021	118
21-22	0.029	0.027	0.023	45



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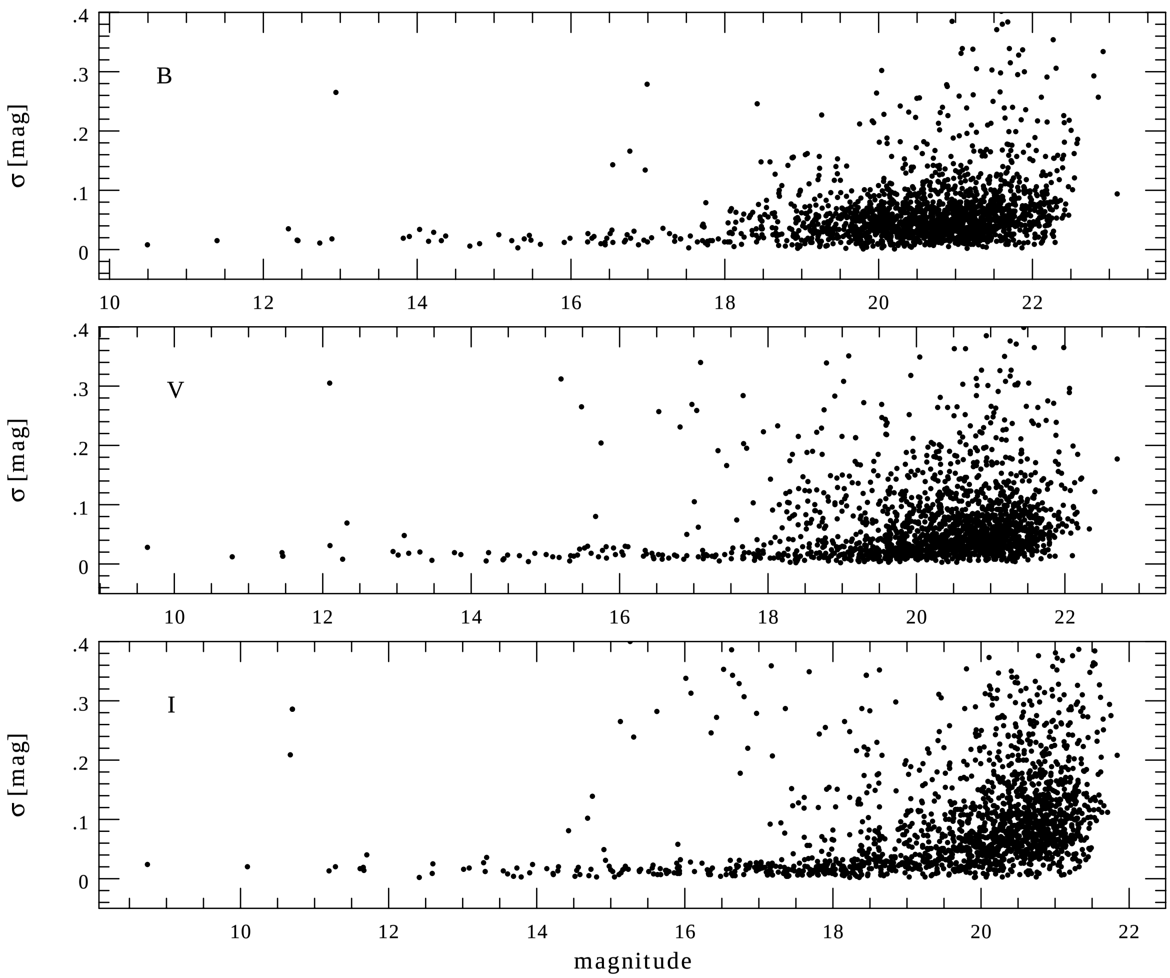
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